PALEOMAGNETIC DETERMINATIONS OF A PRECAMBRIAN AND A TERTIARY DIKE OF THE LOCH TORRIDON REGION OF SCOTLAND

A Thesis submitted in partial fulfillment of the requirements for the degree Bachelor of Science in the College of Mathematics and Physical Sciences of The Ohio State University.

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Abstract

A paleomagnetic investigation of a metamorphosed Post-Scourian basic dike (Precambrian) of the Loch Torridon area of Scotland indicates a virtual geomagnetic pole at 10.16°N, 79.04°E with a precision factor (K) of 411.88 and a cone of confidence (alpha 95) of 1.89°. The stable remnant magnetization of the samples is the result of thermoremnance acquired during the Laxfordian Orogeny, 1,600 m.y. to 1,200 m.y. ago. The investigation of a Tertiary dike of the Loch Torridon area produced no reliable pole position due to the high susceptibility to viscous magnetization shown by the samples and their failure to retain a stable remnant magnetization.

Acknowledgments

I wish to thank Dr. Hallan C. Noltimier for his collection and contribution of the oriented hand samples; for his instruction on paleomagnetic techniques of investigation; and for his assistance in data interpretation.

I also wish to thank Martin Kopacz for his assistance in data interpretation and for the use of his computer programs. Dr. Tim Smith has my appreciation for his assistance in paleomagnetic technique, and Donald Cooke has my thanks for preparing the hand samples and the thin sections I used in this investigation.

Dr. George Moore also has my appreciation for his assistance in thin section interpretation.

I wish to thank the Department of Geology and Mineralogy for the use of equipment and computer time.

Purpose

The purpose of this investigation was:

(1) determine the magnetic properties of the samples.

(2) determine the inclinations and declinations of the stable remnant magnetization (SRM) of the samples.

(3) find paleomagnetic pole positions from the inclinations and declinations of the SRM.

(4) relate the paleomagnetic pole positions to the geologic history of Great Britain and Scotland.

It is hoped the information obtained from this investigation will be useful in understanding the tectonic history of Scotland.

Foreword

The samples were collected in the Loch Torridon area of Scotland by Dr. Hallan C. Noltimier in 1974. He collected samples from what he believed to be a Devonian basic dike and from a Tertiary basic dike recently exposed in a road cut. The hand samples were oriented in the field by magnetic compass and marked in an appropriate fashion. Two hand samples of the "Devonian" dike were collected and shall be known in this report as "Diabaig". Three hand samples were collected from the Tertiary dike and shall be known as "Torridon" in this report.

The hand samples were cored and the NRMs (natural remnant magnetizations) measured in the Spring of 1975 by Donald Cooke. Cooke prepared seven and eight cores respectively from the two Diabaig hand samples and twelve, six, and seven cores respectively from the three Torridon hand samples. Table I-1 lists the results of the Diabaig NRMs measured by Cooke, and table II-1 lists the results of the Torridon NRMs measured by him.

In the Autumn of 1975, the analysis of the Diabaig and Torridon cores was undertaken as a senior thesis by the author.

Geography and Geology of the Loch Torridon Area and the Locations of the Precambrian and Tertiary Dikes.

Loch Torridon is on the northwest coast of Scotland (figure 1). It is in the southern part of what is known as the Northwest Highlands.

The basement rock in the Loch Torridon area is the Lewisian Gneiss. This gneiss is divided into the Scourian phase (also Scourian Orogeny or Complex), 2,600 m.y. old to 2,200 m.y. old, and the Laxfordian phase (also Laxfordian Orogeny or Complex), 1,600 m.y. old to 1,200 m.y. old. In some areas the Scourian is unaffected by the Laxfordian. In other areas, including Loch Torridon, the Laxfordian is superimposed over the Scourian.

Between these two phases of metamorphism, basic dikes known as the Post-Scourian basic intrusions (figure 2) were intruded. According to Janet Watson (in Craig, 1965, page 68),

> "In the mainland belt, the dykes maintain a constant north-west or west-north-west trend over some 2,000 square miles and occur at the rate of at least three or four to the mile. The wide distribution, regular spacing, and parallel orientation of the dykes suggest that they belong to a

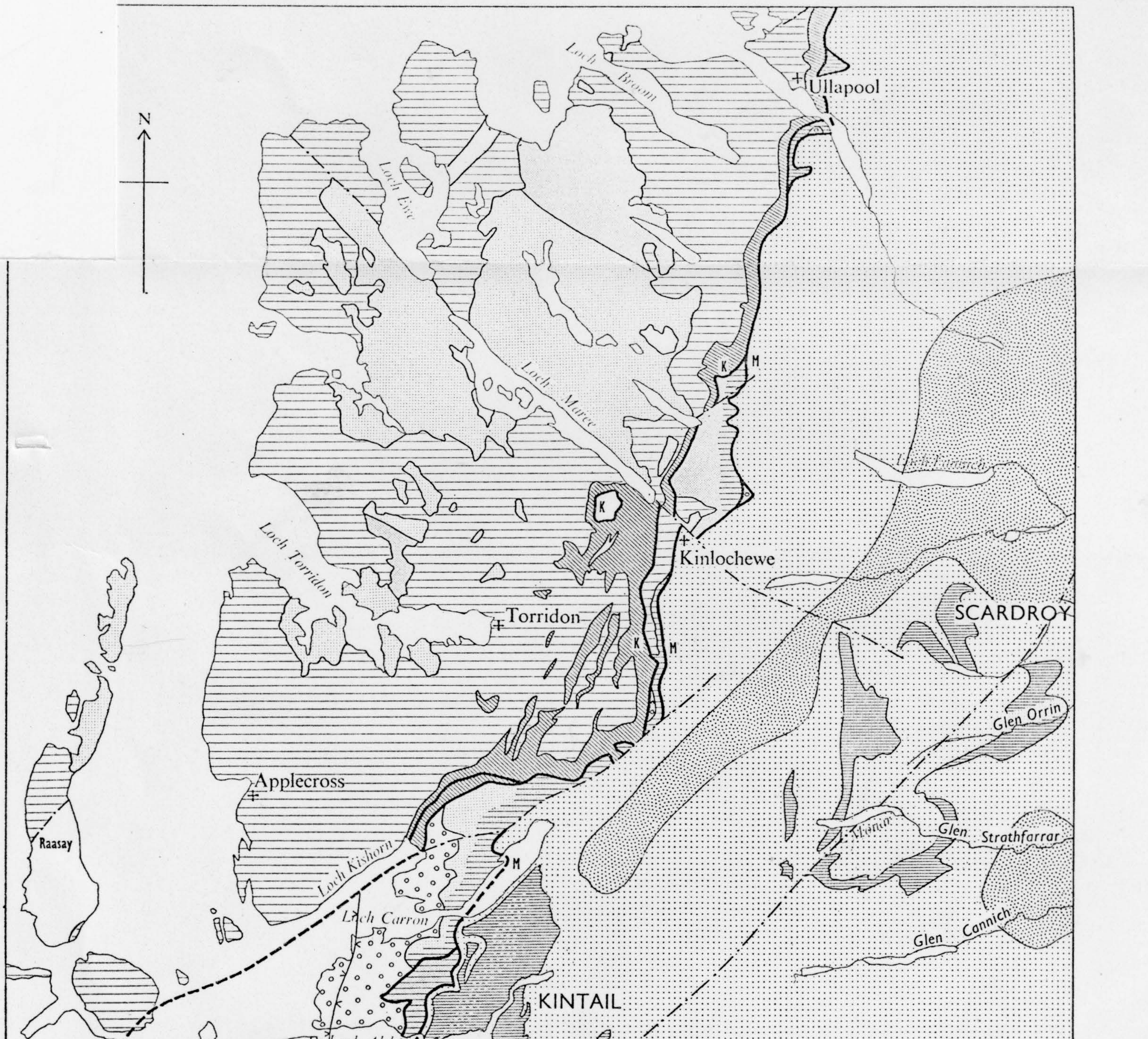


FIG. 3.4. Map to show distribution of Moine and Lewisian rocks in the part of the NW. Highlands that has been reinvestigated in recent years. After Ramsay, *in* Johnson and Stewart (1963).

: p. 86]

(from Craig, 1965)

(figure 1)

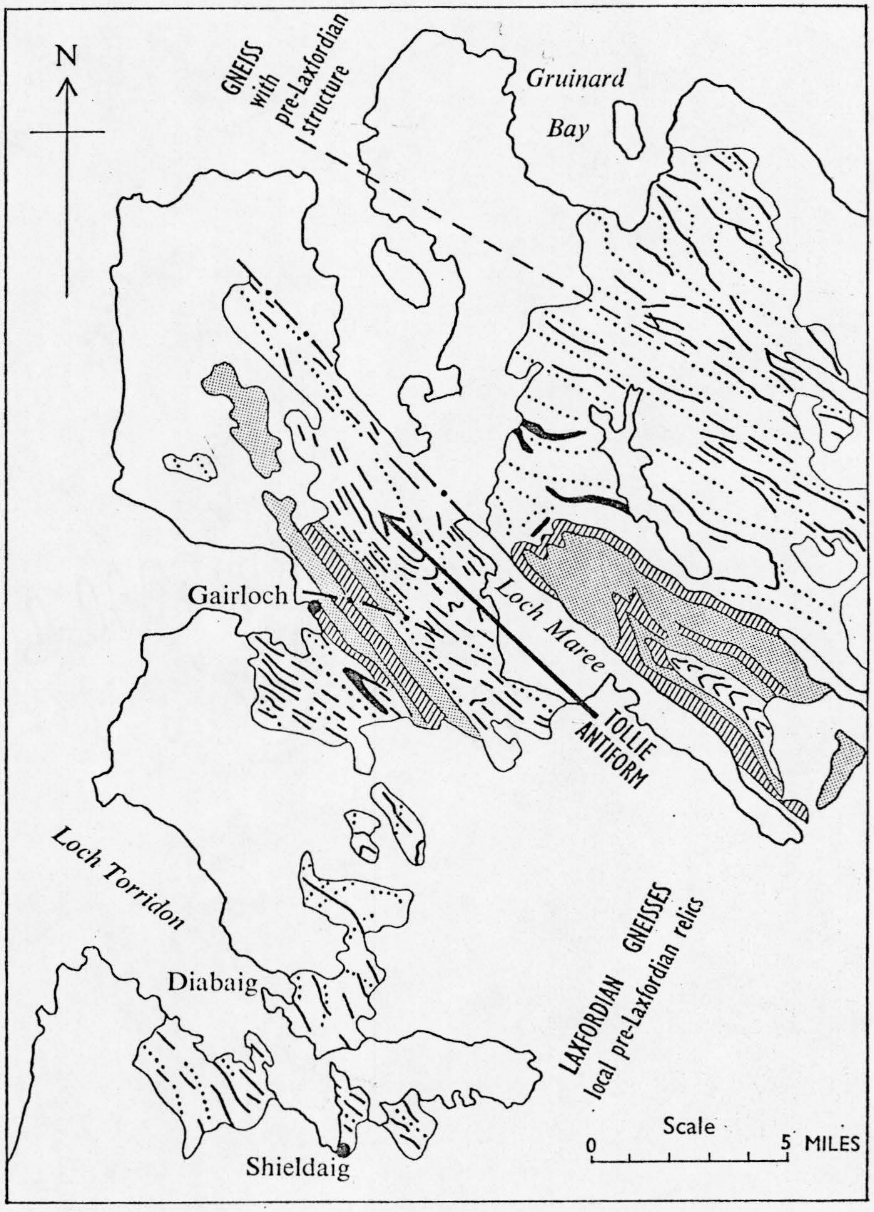


FIG. 2.6. Sketch-map of the southern part of the mainland belt, based on Geological Survey publications. Dotted lines, trend of banding in gneisses. Solid lines, post-Scourian basic dykes. Diagonal lines, metasediments and dotted areas basic sheets in the Loch Maree Series.

(Janet Watson in Craig, 1965)

(figure 2)

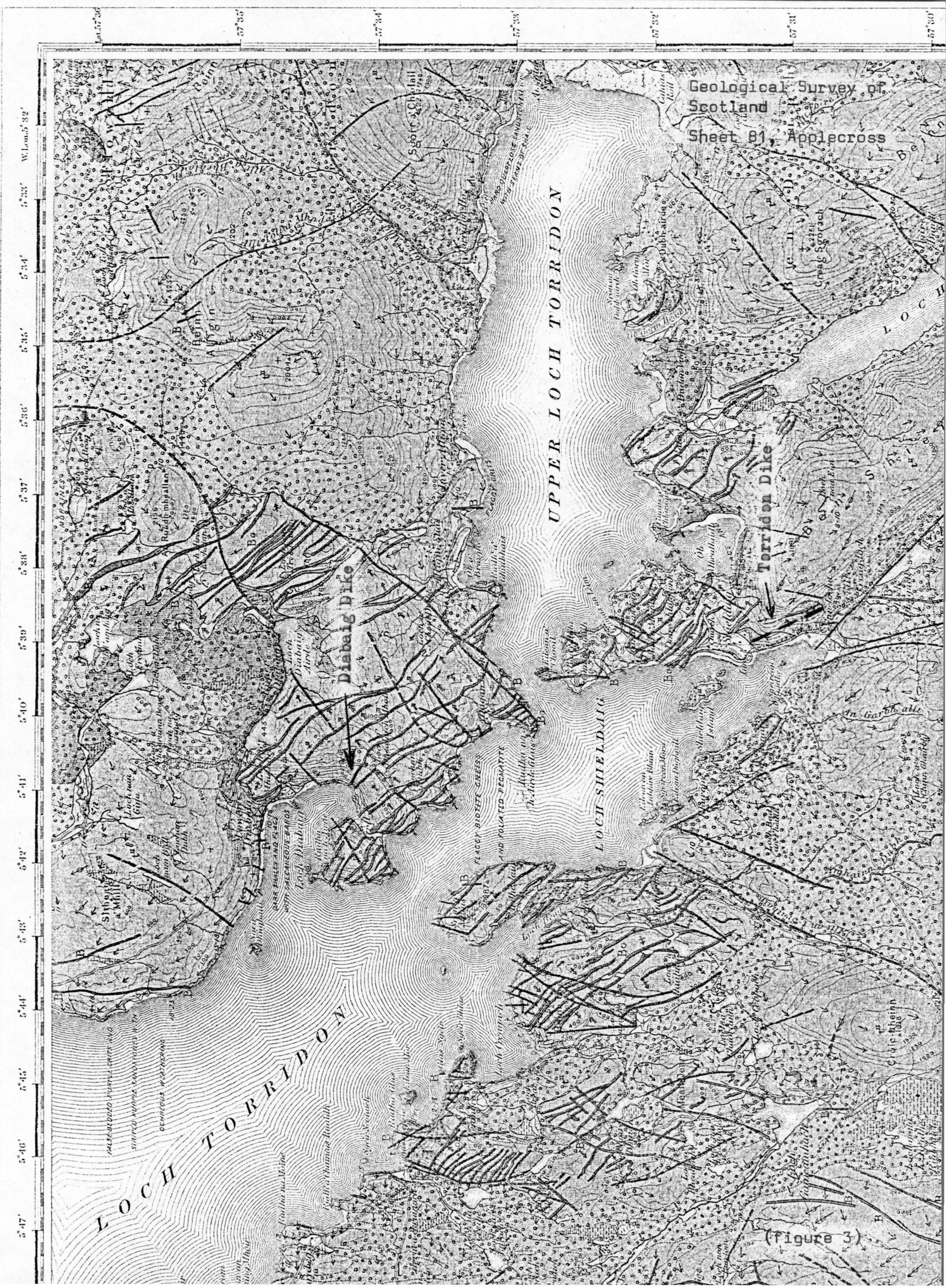
regional swarm controlled by general crustal conditions rather than to swarms connected solely with local igneous centers."

The dike from which the Diabaig samples (figure 3) were collected is mapped as a Post-Scourian basic intrusion on sheet 81 of the Geological Survey of Scotland. This places the age of the Diabaig samples not in the Devonian but between 2,200 m.y. old and 1,600 m.y. old with metamorphism affecting the dike between 1,600 m.y. ago and 1,200 m.y. ago.

The Late Precambrian Torridonian sediments lie unconformably on the Lewisian Gneiss in the Loch Torridon area. In the Northwest Highlands these sediments are unaffected by any metamorphism. Near Loch Torridon, the Applecross group of the Torridonian sediments rests directly on the Lewisian basement. The Applecross group is composed of red and brown arkosic grits (Johnson, in Craig, 1965).

The Loch Torridon area appears unaffected by the great events occurring to the southeast beginning in the Early Paleozoic. Large scale thrusts, faults, metamorphism, and intrusions can

APPLECROSS _ SHEET 81



(figure 3)

be found in this direction. Loch Torridon is in the foreland of the Moine thrust, the edge of which is only ten to fifteen miles to the southeast. This thrust displaced metamorphosed Torridonian sediments (the Moine schist) tens of miles toward the northwest. Futher southeast is the Great Glen fault. Northern Scotland was moved 65 miles southwest along this fault during the Late Devonian. The Loch Torridon area does not appear to be appreciably altered by any of these major events.

The dike from which the Torridon samples (figure 3) were collected was intruded into the Applecross group during the Tertiary. The Tertiary was a time of widespread intrusions in Scotland and Ireland. This dike is probably related to the large complex of intrusions on the Island of Skye, twenty miles toward the southwest (figure 4). Figure 5 is a photograph of this dike.

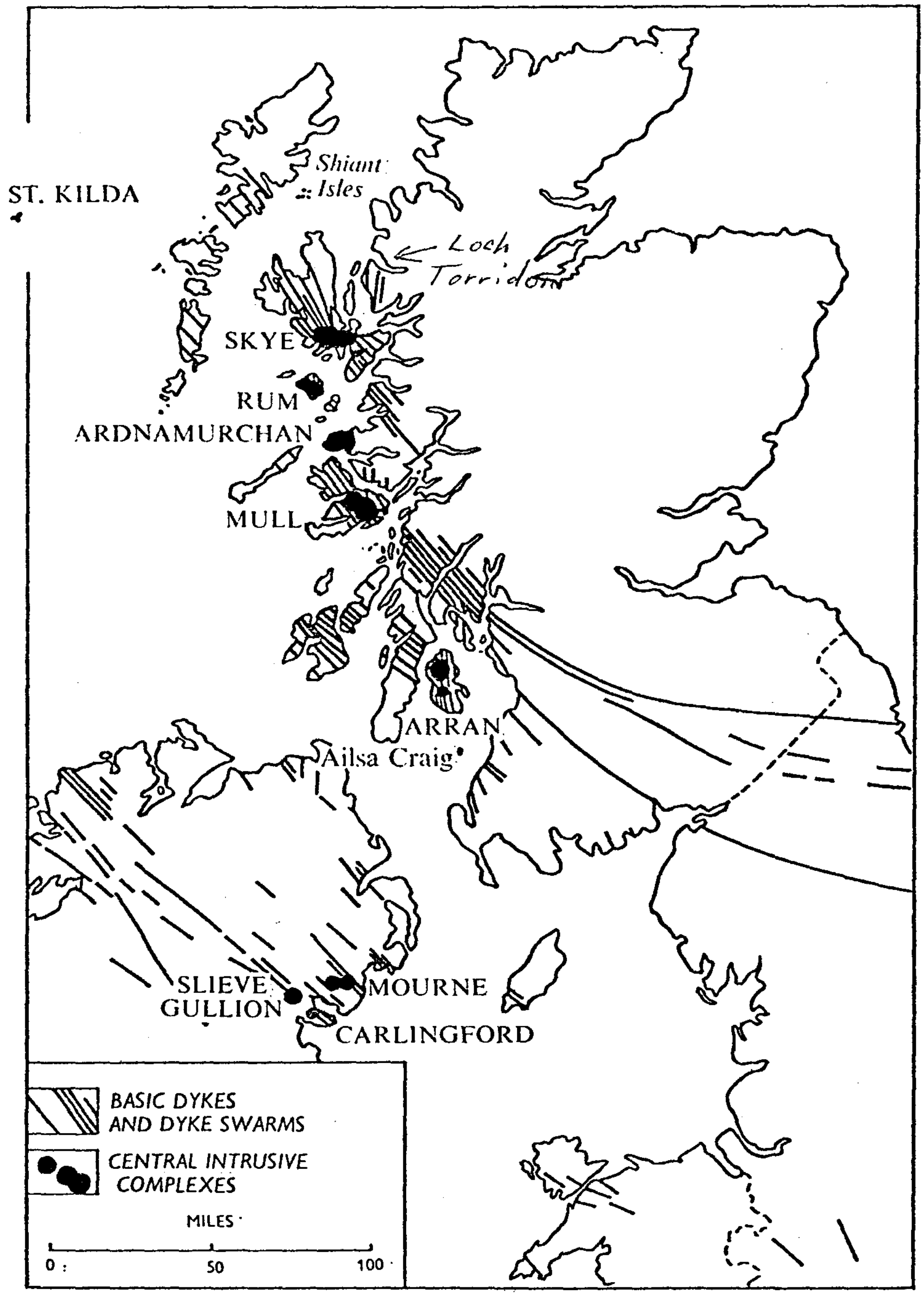


FIG. 13.2. Distribution of Tertiary north-west dykes in relation to Tertiary plutonic districts of Scotland and Ireland. Redrawn from Richey, Thomas *et al.* 1930, Fig. 4.

(from Craig, 1965)

(figure 4)

Torridon dike, Loch Torridon,
Scotland

(Noltimier, 1974)

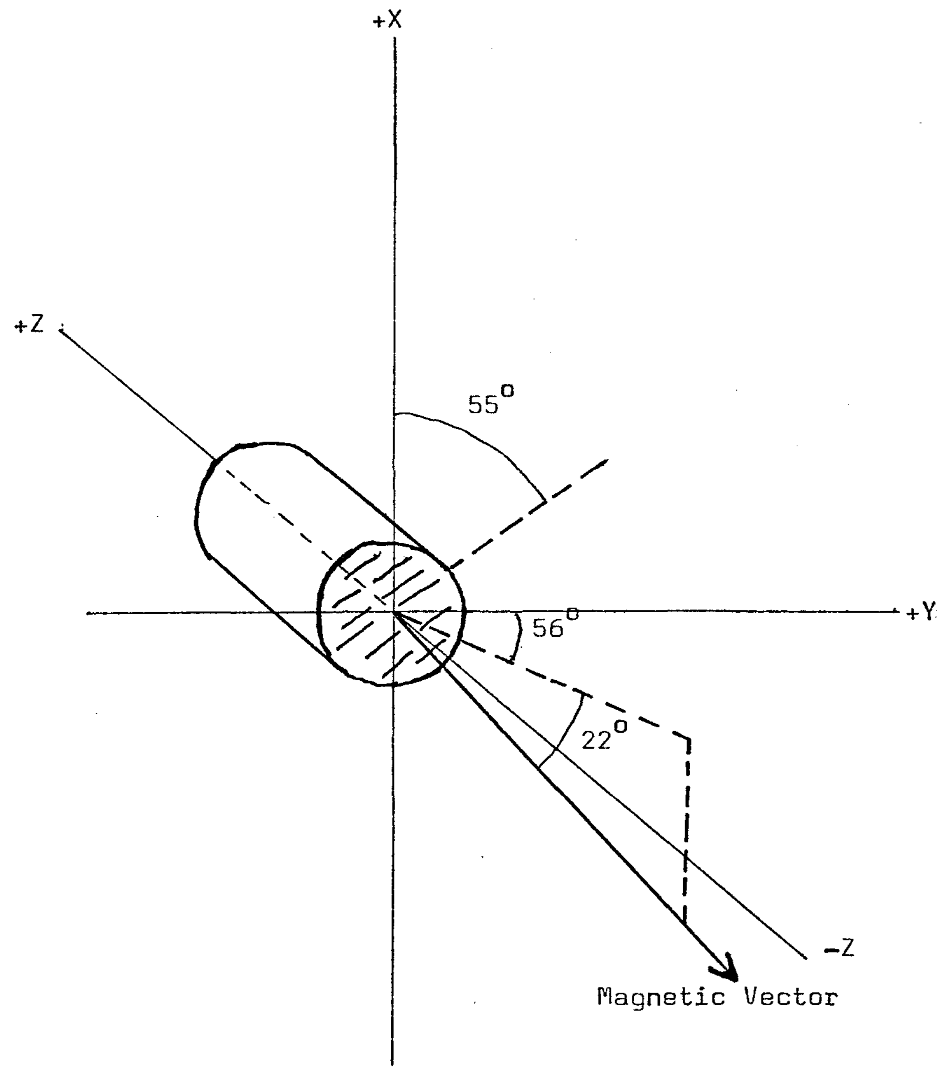
(figure 5)

Petrology of the Diabaig and Torridon Samples

The Diabaig samples are a dark gray, medium-grained hornblende schist with foliation parallel to the Z axis (figure 6) of the cores. After demagnetization, a thin section was prepared from core D1FA. It showed a medium grained, plagioclase-hornblende schist with quartz and biotite also present. Twinning is absent in the plagioclase except for faint "ghosts" of twinning in a few grains. Pyrite and apatite are present in small amounts. No magnetite is discernible.

The Torridon samples are a gray, fine grained porphyritic basalt with phenocrysts of plagioclase and phenocryst sized cavities filled with secondary calcite. A thin section was prepared from core S1BB. The rock has a groundmass of equal parts of plagioclase and augite with perhaps 5% magnetite. The plagioclase phenocrysts make up 5% of the rock and are 2-3mm in length. Another 5% of the rock is composed of secondary calcite filling subhedral cavities 1-3mm in size. The edges of these cavities show a brownish mineral that is perhaps serpentine or iddingsite. A few grains of magnetite slightly larger than in the groundmass are also present.

Position of the Stable remnant magnetic vector of the Diabaig samples relative to the foliation. (foliation parallel to the Z axis)

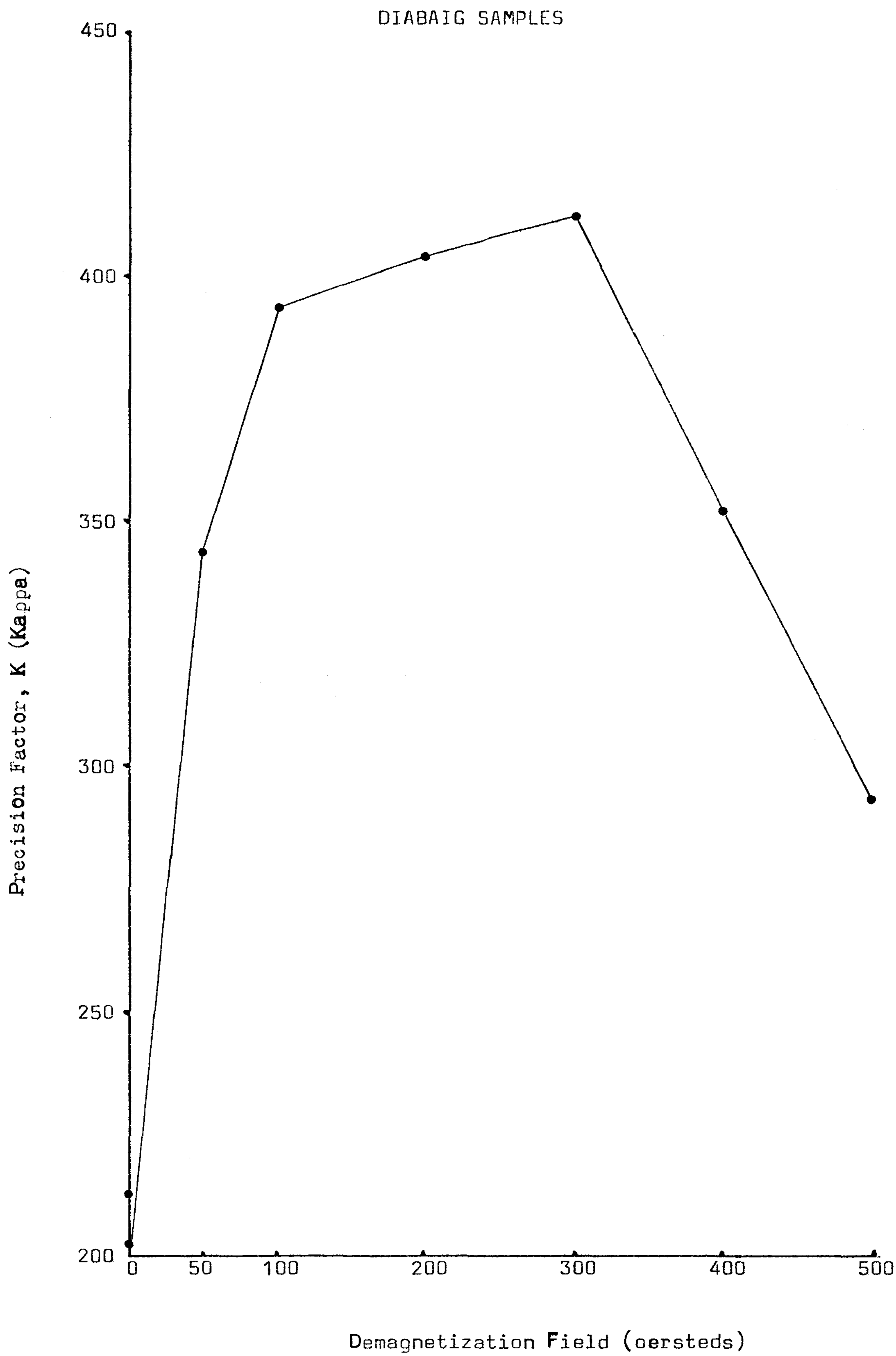


(figure 6)

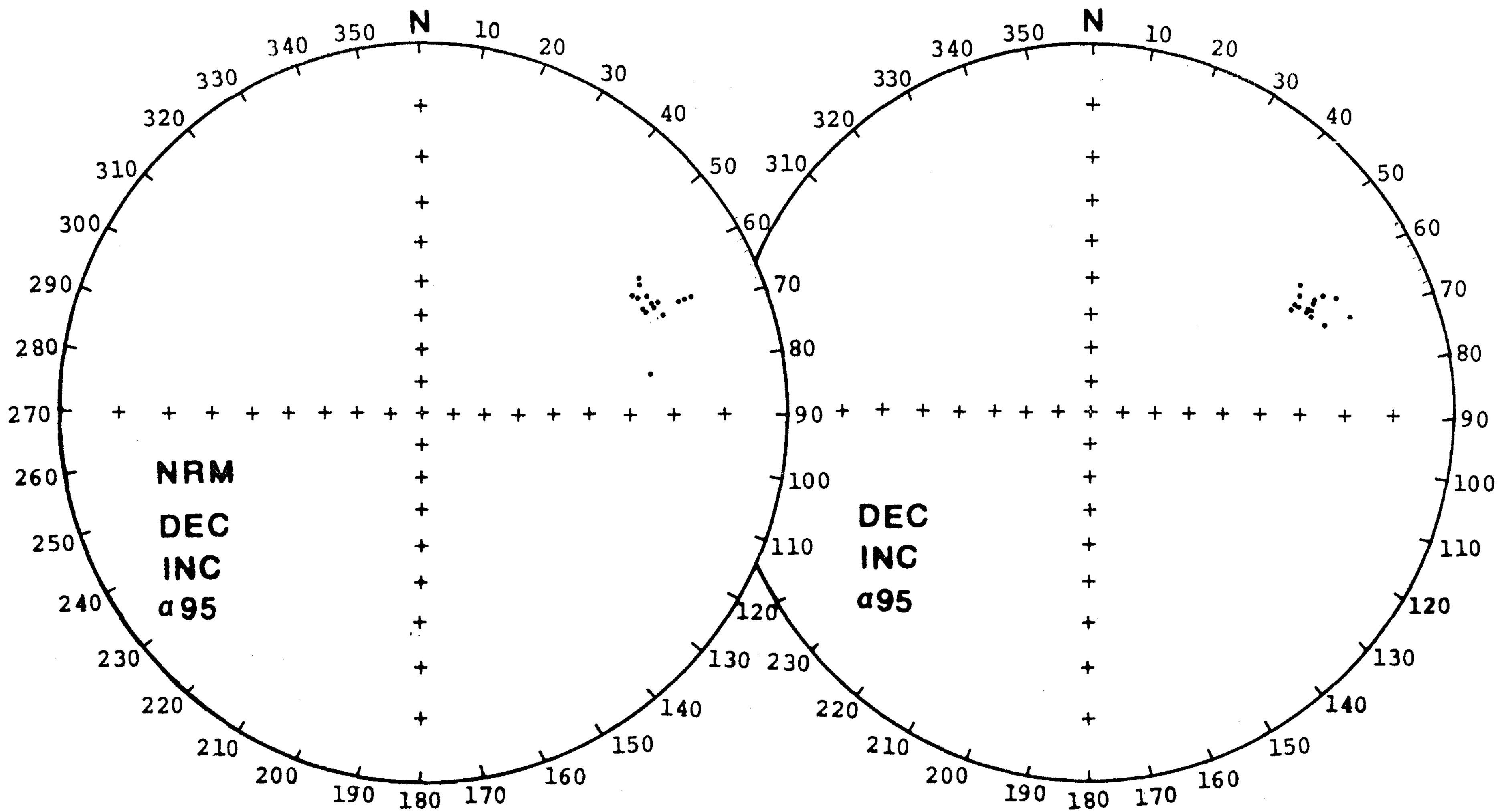
Diabaig

The NRMs of the Diabaig cores were measured in the Autumn of 1975 using a Schonstedt spinner magnetometer. Table I-2 lists the results of these measurements. The cores were stored randomly for over four months between the first measurement of the NRMs by Cooke and this second measurement. The mean declination for the site changed from 64.57° to 65.73°. The mean inclination changed from 22.42° to 20.51°. This indicated the Diabaig cores were relatively free of VRM (viscous remnant magnetization).

Each core was demagnetized in a 50, 100, 200, 300, 400, and 500 oersted field using a Schonstedt Geophysical Specimen Demagnetizer (single axis alternating field demagnetization unit). Tables I-3 through I-8 list the results. A graph of a precision factor, K (Kappa), verses the demagnetization field (figure 7) shows K increases to a maximum of 411.88 at 300 oersteds of demagnetization. A stereographic projection was used to plot (figure 8) the declination and inclination of each core as calculated from the Autumn NRM measurements. This plot is


DIABAIG SAMPLES
450
400
350
300
250
200
0
50
100
200
300
400
500
Precision Factor, K (Kappa)
Demagnetization Field (oersteds)

(figure 7)



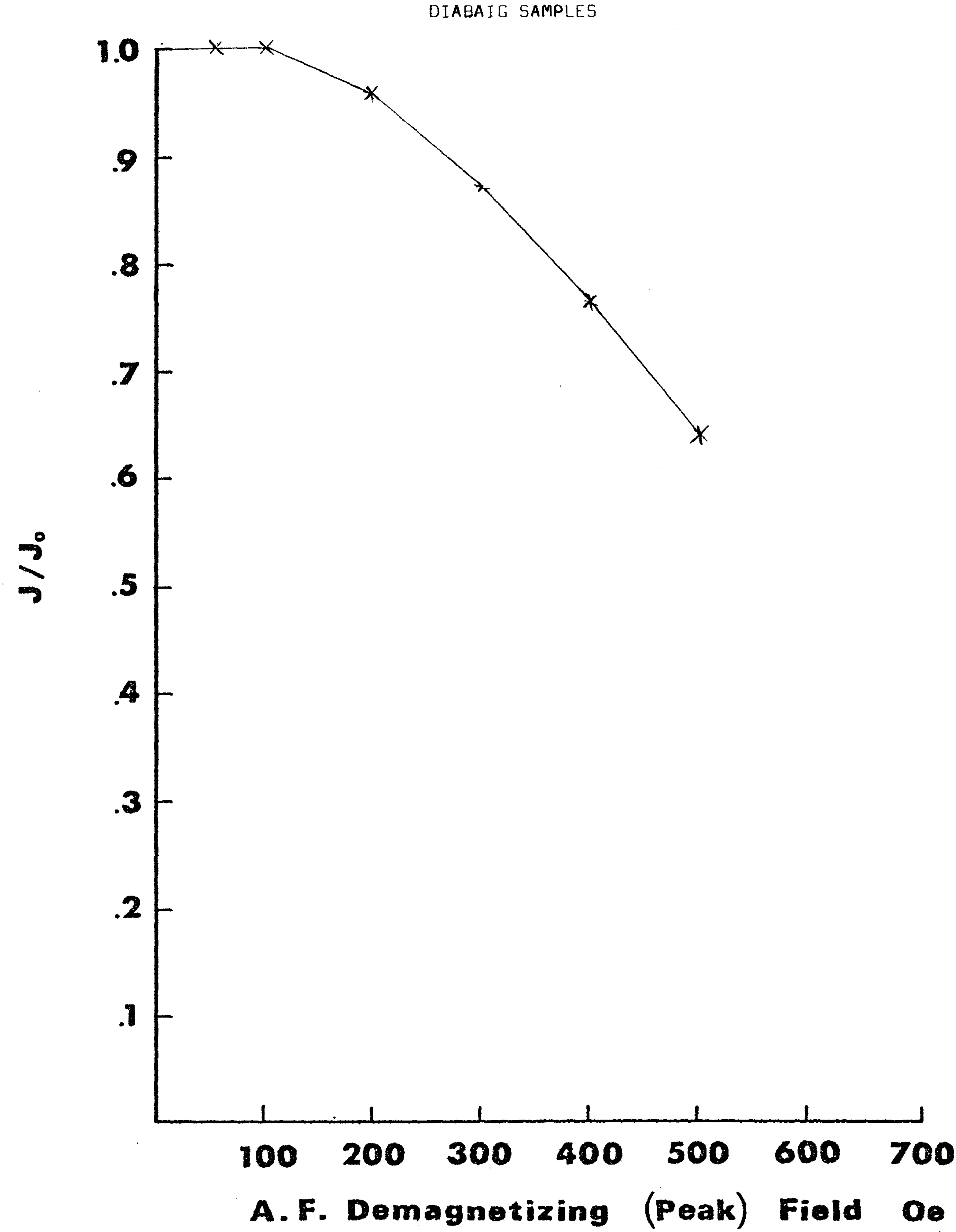
NRM and 300 oersted values of Declinations and Inclinations from the Diabaig samples.

(figure 8)

fairly well clustered and consistent with the calculated cone or confidence (alpha 95) of 2.70°. The declination and inclination of each core as calculated at the 300 oersted level of demagnetization was also plotted. The cluster of the declinations and inclinations has increased and the calculated alpha 95 has decreased to 1.89°.

The mean normalized decay curve was plotted as J/J_o verses the demagnetization field (figure 9). J_o is the measured intensity prior to demagnetization and J is the intensity after demagnetization at the field indicated. The graph indicates the Diabaig cores have a high coercivity and are resistant to demagnetization in even the 500 oersted field. All the Diabaig cores were measured at intensities of 3×10^{-3} emu/cm^3 or 1×10^{-3} emu/cm^3.

Because the cores are from a foliated metamorphic rock and have been subjected to pressure, a test was made for magnetic anisotropy. Dr. Noltimier tested cores D2DA, D2DB, and D2EB using a magnetic susceptibility bridge. The mean susceptibility was found and the anisotropy was calculated from it for three directions in the core in relation to the plane of foliation.


DIABAIG SAMPLES
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
J / J₀
100
200
300
400
500
600
700
A. F. Demagnetizing (Peak) Field Oe

(figure 9)

$(k_1 - \bar{k})/\bar{k}$ is equal to +20%, $(k_2 - \bar{k})/\bar{k}$ is equal to -15%, and $(k_3 - \bar{k})/\bar{k}$ is equal to -5% where $\bar{k}$ is the mean susceptibility, k_1 is parallel to the Z axis of the cores, k_2 is perpendicular to the foliation, and k_3 is perpendicular to k_1 and in the plane of the foliation, This anisotropy is fairly large but is not enough to preclude further consideration of the Diabaig samples.

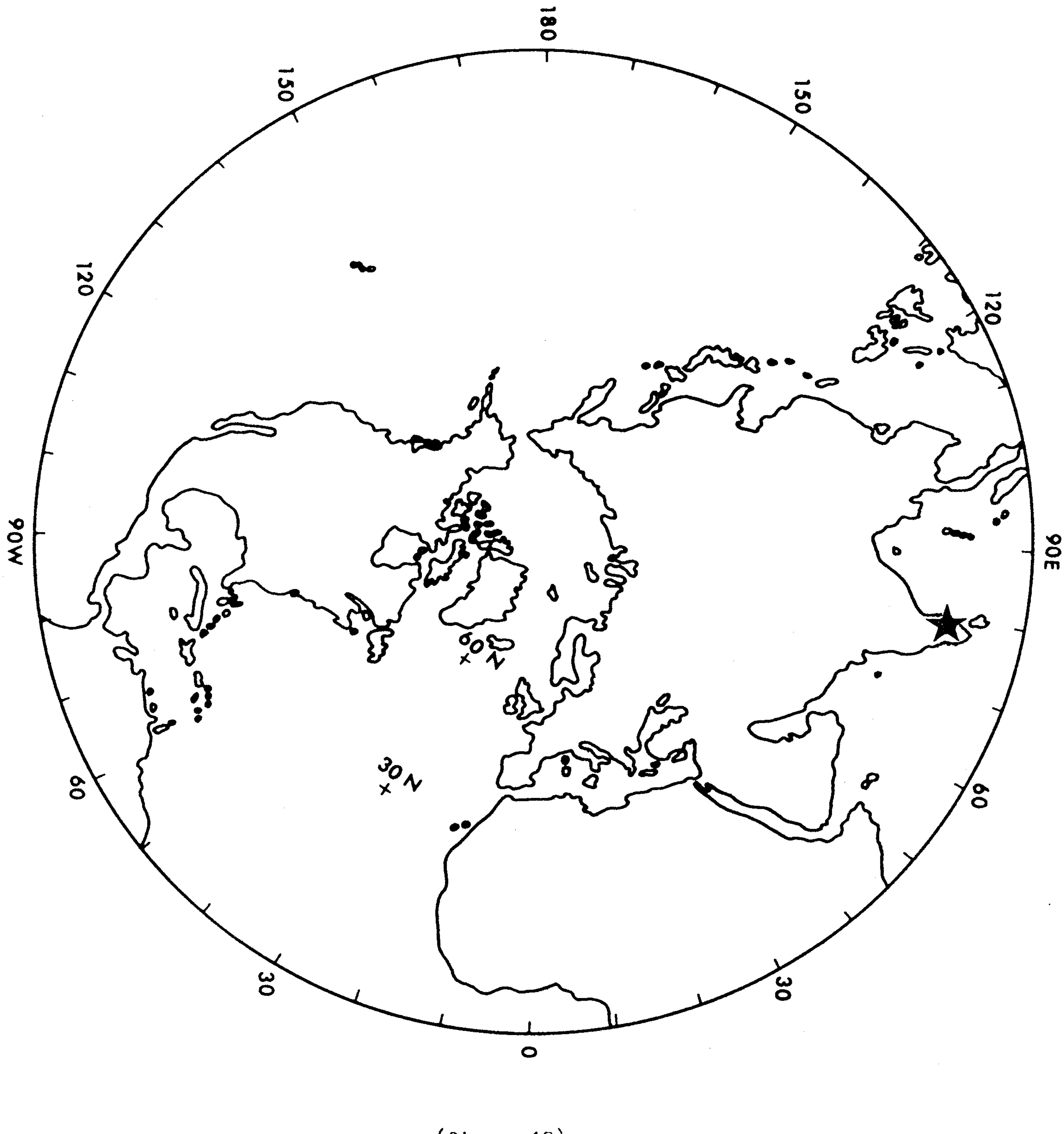
The declination and inclination calculated for the Diabaig cores at 300 oersteds (table I-6) are 64.12° and 22.20° respectively. This gives a virtual geomagnetic pole position of 23.48°N, 100.53°E. The samples from which the cores were prepared were oriented in the field using a magnetic compass. The field notes of Dr. Noltimier give the dike from which they came a strike of N 90°E. This dike, however, is mapped on sheet 81 (figure 3) as striking S 65°E. This indicates the orientations recorded in the field notes are incorrect due to an anomaly in the present magnetic declination near the dike. This error is easily corrected by rotating the calculated declination 25° clockwise (the inclination is not affected). This gives a new declination of 89.12^{o} with a new pole position of 10.16^{o}N, 79.04^{o}E (figure 10). This pole position was compared to the Precambrian apparent polar-wonder path for Scotland and the Baltic shield (figure 16). The pole position for the Diabaig samples is closest (approximately 30^{o}) to this polar-wonder path where the path is shown to be 1,550 m.y. old.

There are many factors to consider in evaluating this pole position. The mineral that carries the remnance must be considered. The type of remnant magnetization must also be considered. The anisotropy of the sample must be evaluated with respect to the other factors.

The remnance of the samples is probably carried by very small crystals of magnetite. The samples were originally intruded as a dike. Magnetite occurs in many dikes and can have quite small crystalline size near the edges of a dike. The very hard remnance of the samples also indicates that magnetite is present in perhaps single domain size.

Very fine grained magnetite would eliminate Pressure remnant

Virtual Paleomagnetic pole position
for the Diabaig cores



(figure 10)

Diabaig pole position

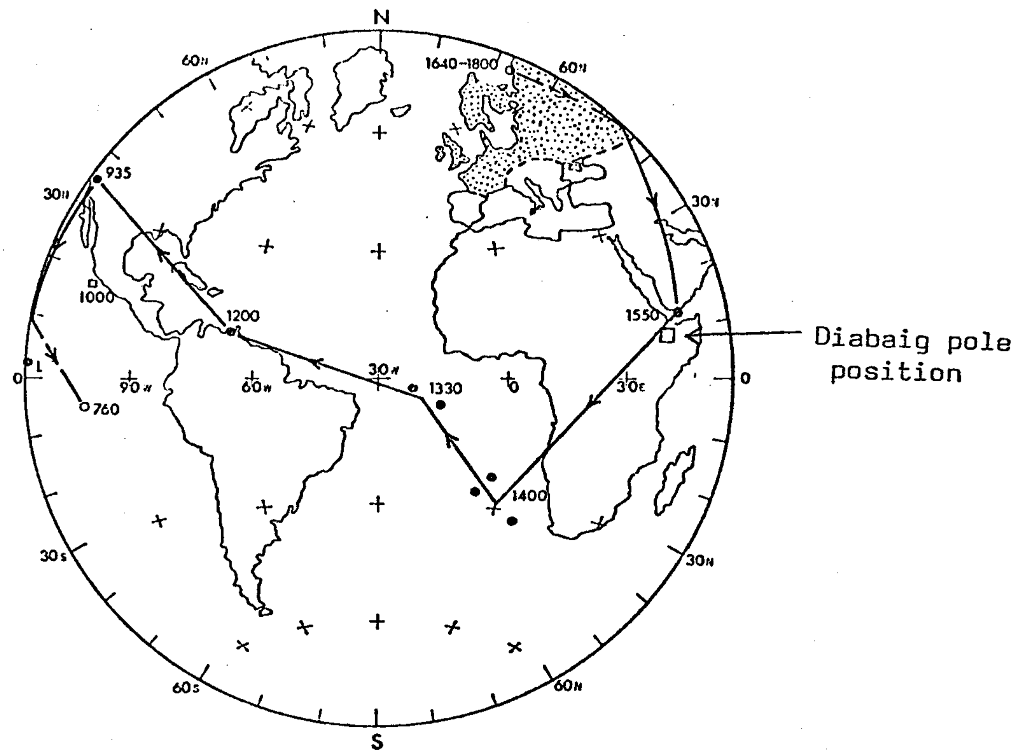


FIGURE 113 Precambrian apparent polar-wander path for Scotland and the Baltic shield. Equatorial equal area projection, solid lines and symbols refer to the projection shown, open symbols and dashed lines refer to points on the other half of the globe. The square is a single pole from the Russian platform. Ages in My are indicated at various points.

(from McElhiny, 1973)

(figure 16)

magnetization (PRM) as a likely source of stable remnance. According to McElhiny (1973, p. 51), inordinately high stress is required to produce significant remnance. He states, however, that "Shape anisotropy, however, can give rise to coercivities considerably greater than this (450 oersted)."

The shape anisotropy of the magnetite grains in the sample can be analyzed by using the values of magnetic anisotropy already mentioned. "The degree of anisotropy A_n is expressed as the ratio of maximum to minimum susceptibility." (McElhiny, 1973, p. 65) This gives the Diabaig cores a ratio of 1.41 or 41% anisotropy. McElhiny states (1973, p. 67) the maximum deflection of a 50% anisotropic rock is only 11.6°. This would indicate that shape anisotropy is not significant in causing the stable remnance of the samples.

Thermoremnant magnetization (TRM) is the most probable source of the stable remnance of the Diabaig cores. TRM is acquired parallel to the earth's magnetic field as the rock cools past its Curie temperature. The Diabaig samples would have acquired their TRMs sometime during the Laxfordian Orogeny. The date of this period of metamorphism (1,600 m.y. ago to 1,200 m.y. ago) roughly agrees with the date obtained from the polar-wonder path (1550 m.y. ago). The magnetic anisotropy of the cores would probably at a maximum deflect the thermoremnance approximately 10°. If the Diabaig cores contain single domain magnetite, the TRM would be very stable.

Torridon

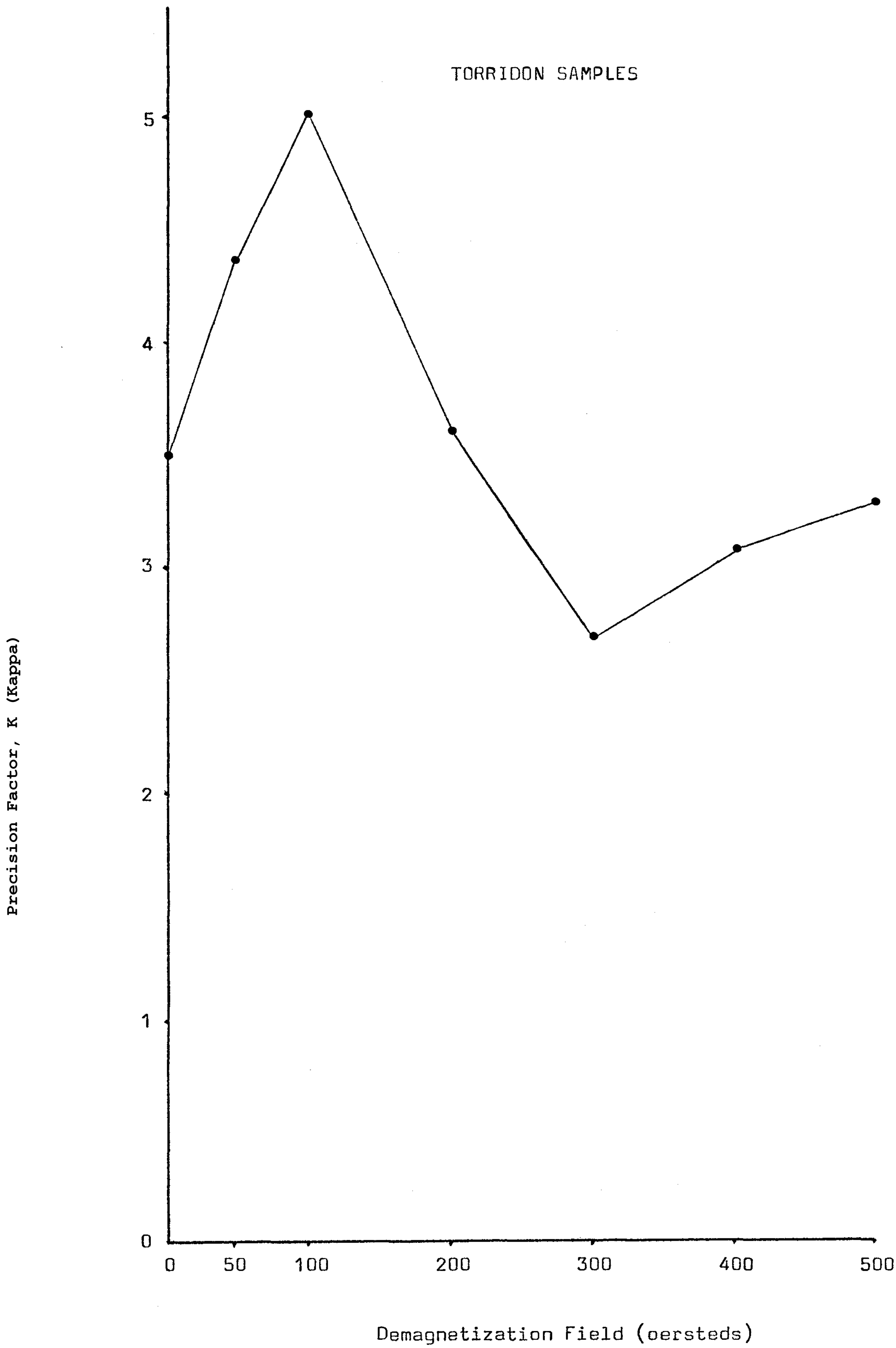
The NRMs of the Torridon cores were measured in the Autumn of 1975. Table II-2 lists the results of these measurements. The cores were stored randomly for over four months between the first measurements of the NRMs and this second measurement. The mean declination for the site changed from 302.89^{o} to 278.56^{o}, and the mean inclination changed from 70.81^{o} to 69.47^{o}. This indicated the Torridon cores were somewhat subject to viscous magnetization. The cores also seemed magneticaly inhomogeneous.

Demagnetization of the twelve cores from the first hand sample was then attempted at 100 oersted intervals. After demagnetization in a 200 oersted field, cores S1CB, S1DB, and S1DC could not be measured in the spinner magnetometer until approximately ten minutes had passed. Core S1CC could not be measured after demagnetization in a 300 oersted field. When these cores were placed in the spinner magnetometer immediately after demagnetization, the needles on the meters would not come to rest long enough to give a reliable reading. The readings that were taken were not repeatable.

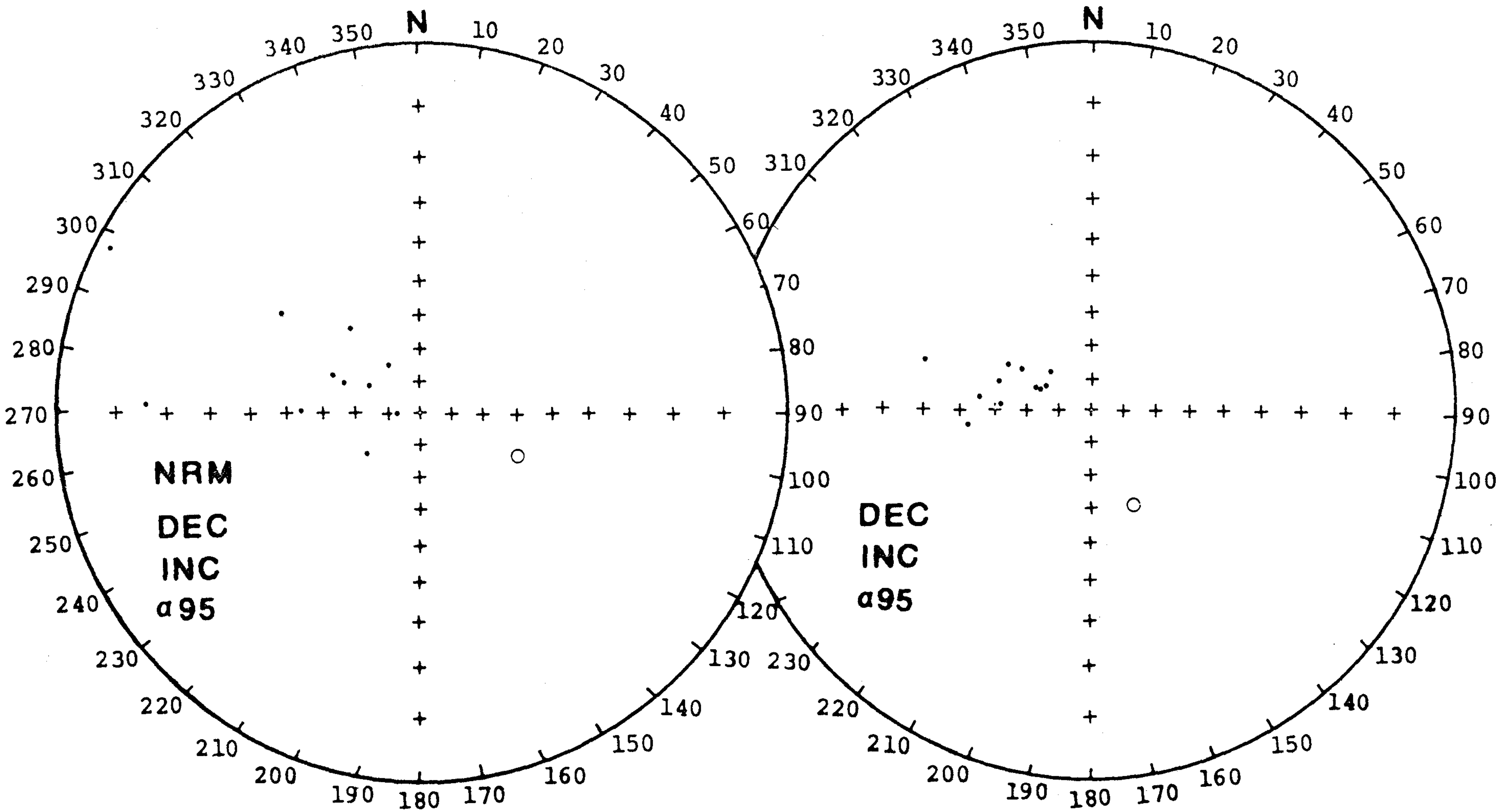
After ten to fifteen minutes this effect disappeared and the cores could be measured. When the cores were again demagnetized in the same intensity field, the effect again appeared and disappeared, but the readings were not the same as before.

Table II-3 lists the NRMs for the twelve cores of the first hand sample. Tables II-4 through II-9 list the results of the demagnetizations. A graph of K verses the demagnetization field (figure 11) shows that K reaches a maximum of 5.12 at 100 oersteds. The NRM values of the declinations and inclinations of the twelve cores are plotted in figure 12. They show a great amount of scatter as indicated by a calculated alpha 95 of 27.19^{o}. The declinations and inclinations of the cores were also plotted at 100 oersteds of demagnetization. The scatter is not as great but it is still not good as indicated by an alpha 95 of 21.30^{o} (table II-5).

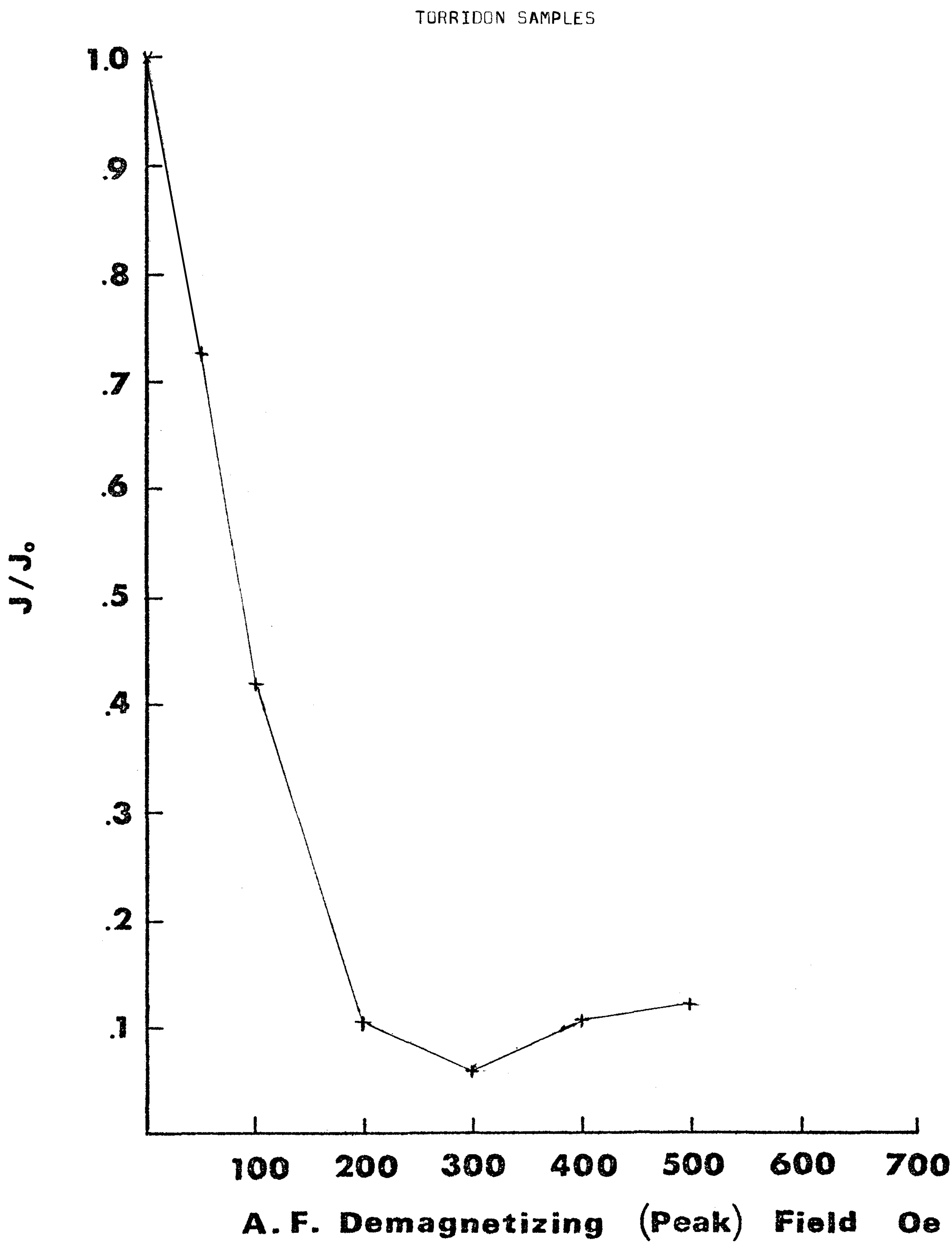
The mean normalized decay curve was plotted (figure 13) as with the Diabaig samples. It indicates that the Torridon samples have a low coercivity. The cores were measured at


TORRIDON SAMPLES
Precision Factor, K (Kappa)
0
1
2
3
4
5
0
50
100
200
300
400
500
Demagnetization Field (oersteds)

(figure 11)



NRM and 100 oersted values of Declinations and Inclinations
from the Torridon samples.
(figure 12)


TORRIDON SAMPLES
1.0
.9
.8
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.5
.4
.3
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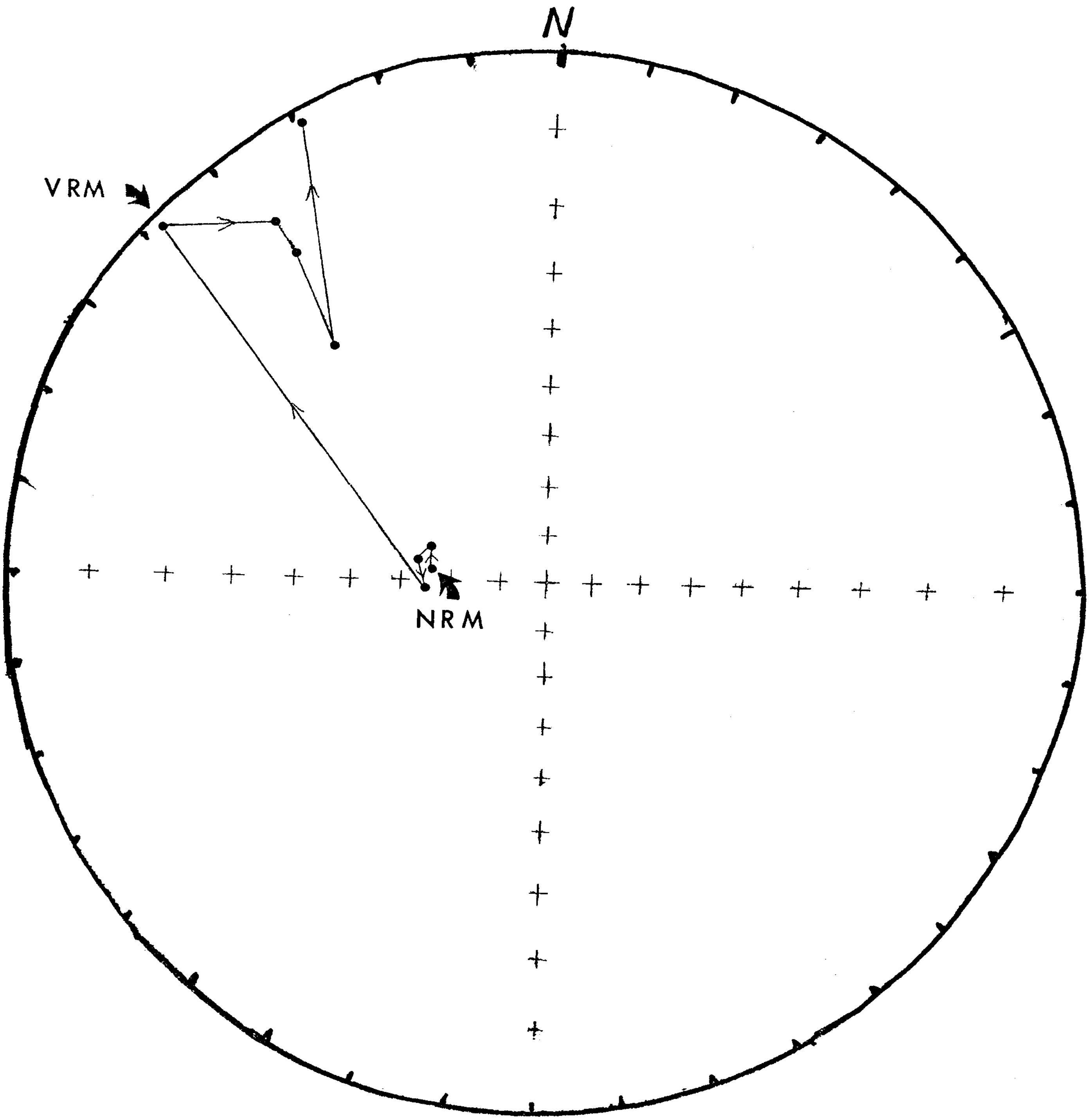
J/J₀
100
200
300
400
500
600
700
A. F. Demagnetizing (Peak) Field Oe

(figure 13)

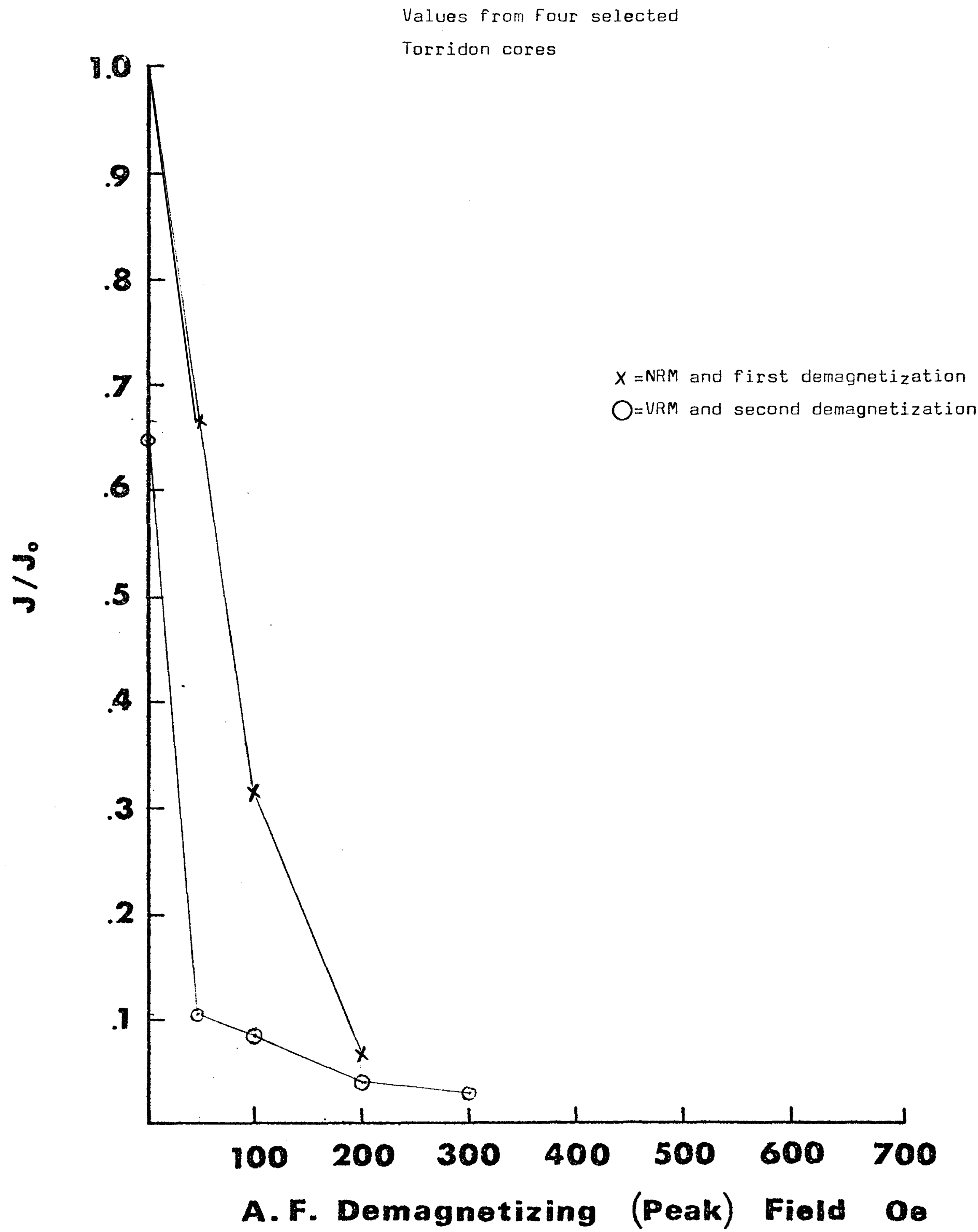
intensities varying from 1×10^{-1}emu/cm^3 to 5×10^{-4}emu/cm^3. Most cores, however, were measured at 1×10^{-2}emu/cm^3.

Because of the odd behavior of four of the cores and the low values of K, the cores were tested for susceptibility to viscous magnetization. Cores S1BB, S1CA, S1CB, and S1CC were placed in a 1 oersted downward field with top up and scratch north for 24 hours. They were then measured and demagnetized at 50, 100, 200, and 300 oersteds. There were no problems encountered in measurement at the 200 and 300 oersted levels. Tables III-1 through III-4 give the NRMs and original demagnetization results for the four cores selected. With only these four cores from the original twelve, K has increased to 57.59 at the 100 oersted level of demagnetization. Table III-5 lists the results from the cores after they had been in the 1 oersted field. K is 297.92 and the declination and inclination has changed greatly (figure 14). Tables III-6 through III-9 lists the results of the second demagnetization of the cores. The K becomes smaller rapidly. The mean normalized decay curve (figure 15) declines much more

Mean Inclinations and Declinations of four selected cores from the Torridon Samples.



(figure 14)


Values from Four selected
Torridon cores
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
J / J₀
X =NRM and first demagnetization
○=VRM and second demagnetization
100
200
300
400
500
600
700
A. F. Demagnetizing (Peak) Field Oe

(figure 15)

rapidly than during the first demagnetizations. Figure 14 shows that the inclinations and declinations of the cores do not return to their former positions after the cores were exposed to the 1 oersted field.

On the basis of their great susceptibility to viscous magnetization and failure to retain a stable remnant magnetization, it was concluded that the declinations and inclinations derived from the Torridon cores were useless as indicators of paleomagnetic pole position. Therefore, the cores from the second and third hand samples were not demagnetized.

Conclusion

The results obtained from the Diabaig samples are quite pleasing. The samples displayed a stable remnant magnetization with high coercivity. The inclinations and declinations of the samples had a high precision factor (K) of 411.88 with a cone of confidence (alpha 95) of 1.89°. The stable remnance of the samples seems to be carried by fine grained magnetite of perhaps single domain size. This stable remnant magnetization is from thermoremnance imparted on the samples during the Laxfordian Orogeny, 1,600 m.y. to 1,200 m.y. ago. The date of 1,550 m.y. ago obtained from the Precambrian polar-wonder path of Scotland agrees with the date of the orogeny. This polar-wonder path is not well enough defined, however, to be able to establish a date for the end of the affects of the Laxfordian Orogeny in the Loch Torridon area. The angle of deflection of declination and inclination caused by the anisotropy of the specimens also would affect any date determined from the polar-wonder path.

The results obtained from this investigation appear reliable. It is regrettable, however, that further investigation of the Diabaig dike could not be undertaken to increase the sample size and find the amount of deflection caused by the anisotropy.

The Torridon samples were found to be poor specimens for paleomagnetic investigation. They seemed inhomogeneous. They had a low coercivity. Most importantly, they failed to retain a stable remnant magnetization. It was not possible to determine a reliable pole position from the samples. The odd behavior of a few of the cores only seems explained by a very short-term decay of viscous magnetization after it is disturbed by demagnetization. Further investigation would be required to determine the cause of the effect with any certainty.

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